Water use of the UK thermal electricity generation fleet by 2050: Part 1 identifying the problem

Quinn, Andrew; Murrant, Daniel; Chapman, Lee; Heaton, Chris

DOI:
10.1016/j.enpol.2017.05.011

Citation for published version (Harvard):
Quinn, A, Murrant, D, Chapman, L & Heaton, C 2017, 'Water use of the UK thermal electricity generation fleet by 2050: Part 1 identifying the problem', *Energy Policy*, vol. 108, pp. 844-858.
https://doi.org/10.1016/j.enpol.2017.05.011

Energy Policy 108 (2017) 844–858

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Water use of the UK thermal electricity generation fleet by 2050: Part 1 identifying the problem

Daniel Murrant[a,*], Andrew Quinn[a], Lee Chapman[b], Chris Heaton[c]

[a] School of Civil Engineering, University of Birmingham, Birmingham, West Midlands B15 2TT, UK
[b] School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, West Midlands B15 2TT, UK
[c] Energy Technologies Institute, Loughborough, East Midlands LE11 3UZ, UK

ARTICLE INFO

Keywords:
Water-energy Nexus
UK energy policy
Water resources
Climate change
Power station cooling

ABSTRACT

The effects of increasing water and energy demand pose a growing threat to national infrastructure strategies. Within the UK there is concern that a future lack of water will compromise the UK's current energy policy to meet an increasing demand for electricity by more thermal generation. This paper investigates this by modelling the water demand of the UK's thermal generation in 2030 and 2050 for several future electricity generation pathways. Unlike previous studies this paper has obtained water abstraction and consumption figures specific to the UK.

While the water demands were heavily pathway dependent this study finds for the thermal generation pathways there is a serious mismatch between the assumed freshwater available at 2030 and 2050, its expected actual availability, and an understanding of the implications this has for future generation costs. It is shown that a solution is to make greater use of the UK's seawater resource. This study finds the emphasis UK energy policy gives to the competing poles of low cost electricity generation and environmental protection will have significant impacts on the cost and make-up of the UK's future electricity generation portfolio. A companion paper will consider the generation cost issues if seawater is not available.

1. Introduction

The interdependencies between the availability of water and the generation of electricity are increasingly posing a threat to many national infrastructure systems (Gu et al., 2014; Hussey and Pittock, 2012; Pacsi et al., 2013; Tran et al., 2014). This is the result of an ever-increasing demand for water and electricity generation associated with a decreasing availability of freshwater for power station cooling water. This reduction in freshwater availability is the result of climate change, increasing demographic issues, and increasingly stringent environmental regulation.

Byers et al. (2014) estimates that up to 90% of water abstracted by power stations is for cooling therefore the cooling method used by power stations dictates their water demand. Once-through cooling uses water to cool a power station's exhaust heat directly and is recognised as the Best Available Technique (BAT) due to its relatively high efficiency, and therefore low cost and CO_2 burn (European Commission, 2001). Of the cooling methods it by far withdraws the greatest volumes of water. There are alternative cooling methods which withdraw less but these are more inefficient and consume more (Byers et al., 2014, 2015; Murrant et al., 2015). Evaporative cooling uses cooling towers and recycles its cooling water, air cooling uses no/negligible water, hybrid cooling systems are a combination of evaporative and air cooling. Although these cooling methods are less water intensive they do carry significant cost penalties (Turnpenny, 2010; Macknick et al., 2011).

For the UK a number of studies have looked at this water-energy nexus issue and the unanimous view was from 2010, through to the 2050s a scarcity of freshwater will increasingly compromise UK thermal power stations' ability to generate electricity (Byers et al., 2014, 2015; Murrant et al., 2015; Schoonbaert, 2012; The Royal Academy of Engineering et al., 2011). From 2010–2050 UK electricity demand is predicted to grow from 384 TW h to a potential 610 TW h (HM Government, 2011; Macleay et al., 2011), with Government policy seeing the means being predominantly an increase in thermal generation (Committee on Climate Change, 2015; DECC, 2015; Government, 2011).

Byers et al. (2014) produced a model framework to quantify the operational water demands of different electricity generation pathways in terms of their water abstraction and consumption demand, per

* Corresponding author.
E-mail address: d.murrant@bham.ac.uk (D. Murrant).

http://dx.doi.org/10.1016/j.enpol.2017.05.011
Received 11 May 2016; Received in revised form 28 March 2017; Accepted 6 May 2017
Available online 27 May 2017

generation technology, per cooling method, per timeframe. The framework could also distinguish between different cooling water resources; the options being freshwater, estuarine and sea water. To obtain information on the water demands of different generation pathways the Byers' framework was used to model the water demands of six possible future UK electricity generation pathway options, see 2.2 Carbon Plan Pathways.

For Byers et al. (2014) the water abstraction and consumption figures used were based on a study carried out by the USA's National Renewable Energy Laboratory (NREL) (Macknick et al., 2011). The authors of this paper obtained access to UK specific water abstraction and consumption figures compiled by the Joint Environmental Program (JEP), and made available by the Environment Agency (EA). For this paper this data is referred to as the UK abstraction and consumption figures.

The aim of this paper is to consider how the future water demands of UK thermal electricity generation in a freshwater scarce environment could impact UK energy policy. This was achieved by using the Byers et al. (2014) framework, and the UK abstraction and consumption figures to attribute, relative to 2010, national abstraction and consumption water demands to the Energy Technology Institute's (ETI) Energy Systems Modelling Environment (ESME) pathways (see 2.1 Energy Systems Modelling Environment (ESME) model) for 2030 and 2050. Given the importance of the Carbon Plan in setting out how future UK energy policy will aim to achieve decarbonisation (HM Government, 2011), the opportunity will also be taken to update the six 2030 and 2050 pathways analysed by Byers et al. (2014).

2. Background to electricity generation pathways modelled

2.1. Energy Systems Modelling Environment (ESME) model

The ETI is a collaboration between industry and the public sector, formed in 2007, to promote the UK's transition to a low carbon economy (Heaton, 2014). The ETI developed the internationally peer-reviewed ESME model to identify technologies likely to be important for creating an affordable, secure, and sustainable energy system. In addition it was also required to meet the UK's 2050 Greenhouse Gas (GHG) emissions reduction target of 80% from their 1990 levels (Heaton, 2014; Energy Technologies Institute, 2016). Besides being used by the ETI's members and academic institutions ESME was used by the Department of Environment and Climate Change (DECC) when developing the UK's Government's Carbon Plan, and by the Committee on Climate Change (CCC) for their review of carbon budgets (Day, 2012; Heaton, 2014).

ESME is a design tool rather than a forecasting tool and adopts a least-cost optimisation Monte Carlo approach to modelling the UK energy system whilst still adhering to a number of specified targets and constraints. These include emission targets, resource availability, technology build rate, and meeting the projected energy demand. It should be noted that ESME is only constrained by CO_2 emissions rather than all GHG emissions, although the expected pathway of all GHG emissions are taken into account when determining the levels of CO_2 allowed (Heaton, 2014).

When modelling the future UK energy system ESME adopts a whole system scope which includes all the major flows of energy: electricity generation, fuel production, energy use for heating, industrial energy use, and transportation of people and freight. A range of technology options are available encompassing all the energy flows above, including power stations, vehicle and heater type, each with a number of input parameters such as available resources, fuel prices and technology costs (Energy Technologies Institute, 2016).

ESME then uses the least cost optimisation method to analyse the various permutations of technology choices. It selects those which produce the least cost energy system out to 2050 whilst still meeting and adhering to the specified targets and constraints. ESME can model its energy system in either five, or 10 year, time steps from 2015 to show the progression to 2050.

Unlike similar UK energy system models such as MARKAL, rather than providing only national outcomes, ESME can model demands and resources at the UK regional level, and show the regional location of its modelled electricity generation infrastructure (HM Government, 2011). As UK energy demand, water demand, and water availability vary regionally, this regional functionality is an advantage that the use of the ESME model brings to this study. Although for the purpose of this paper, and to provide a starting point for this research, only the 2030 and 2050 national outcomes relative to 2010 will be considered here. The key results and outcomes developed using the modelling analysis described in this paper are then built upon in the companion paper to enable analysis on a regional scale to be undertaken (Murrant et al., 2016).

While at the national and regional level ESME is able to provide least-cost and CO_2 emissions optimised generation pathways it is not able to consider the associated water demand of the modelled pathways. With thermal generation being the major 'intended' electricity generator for many ESME pathways, and with future water availability increasingly an issue, this limits ESME's usefulness as a strategic modelling tool. This is a matter which was resolved at the regional scale by this study and is described in more detail in the companion paper.

2.1.1. Monte Carlo approach

Any model has inherent uncertainties particularly one as complex and broad as ESME. Whilst it is impossible to entirely remove these uncertainties ESME uses the Monte Carlo technique to manage and quantify them. Rather than producing a single perturbation ESME produces hundreds, or even thousands, where the input parameters (e.g. energy resources, fuel prices, technology costs) are varied for each according to the probabilistic distribution of the parameter. This was developed by the ETI in consultation with industry experts. As well as showing the range of individual results a final result is produced by taking the mean average of this range.

This approach allows a range of possible future energy systems to be considered. Besides identifying technologies which appear highly likely to contribute to the future energy system, it also identifies those which may depending on how the input parameters change in the future. This approach was felt to be a further benefit of using the ESME model as it helps to identify the range of uncertainty that policymakers have to consider when taking decisions.

2.1.2. ESME pathways

The results produced by ESME, as with any model depend upon the inputs. When ESME is perturbed with standard probabilistic distribution for each input parameter using the Monte Carlo approach the result is referred to as the Monte Carlo (ESME.MC) pathway. It represents ESME's best design make-up of a 2050 UK electricity generation pathway. When modelling the 2050 pathway it focuses on achieving the UK's CO_2 emission reduction, and electricity generation targets at least-cost. As a result the generating technologies selected are found to favour additional nuclear generation, then CCGT +CCS plant supported by renewables, Fig. 1. The ESME.MC pathway finds a large adoption of nuclear generation results in the cheapest overall energy system because it reduces the need for intermittent renewable energy generation which requires expensive storage and balancing infrastructure. This may appear counter intuitive given that a number of proposed nuclear power stations in Europe including Hinkley Point C are over-budget, however this new generation of nuclear power stations are effectively First Of A Kind and therefore costs can be expected to reduce in the future (Csereklyei, 2016). Furthermore by using its' Monte Carlo approach the ESME.MC pathway does consider a range of capital costs for nuclear power stations, some of which foresee budget overspends of almost 50%.

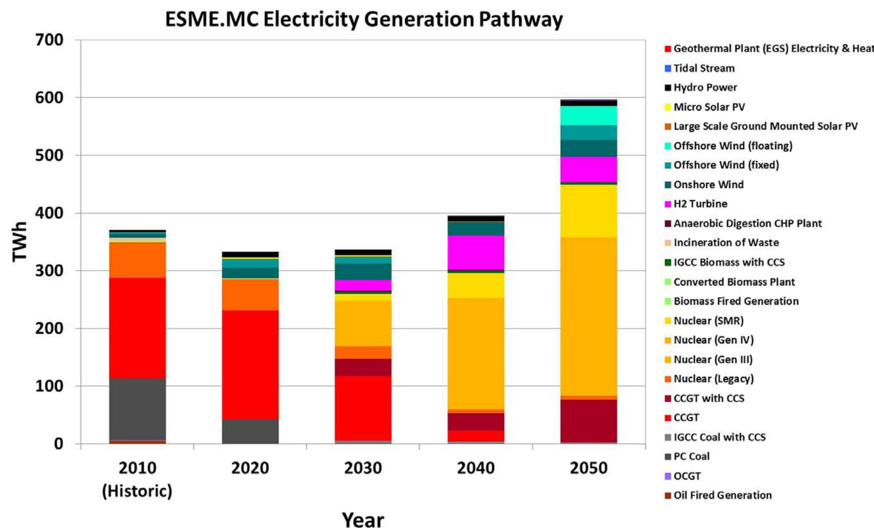

Fig. 1. ESME.MC Electricity Generation Pathway (Energy Technologies Institute 2014).

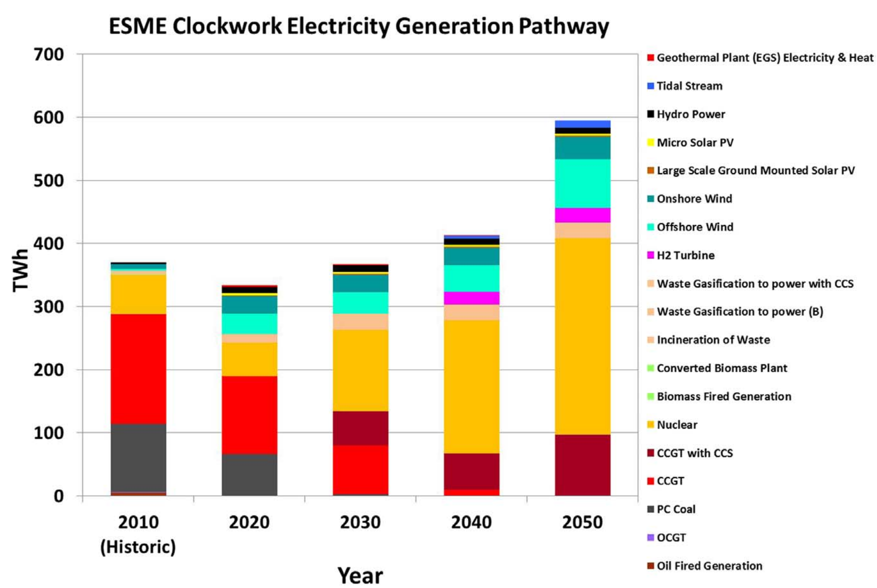

Fig. 2. ESME Clockwork Electricity Generation Pathway (Milne and Heaton, 2015).

ESME can be perturbed in a deterministic way where just a single run is undertaken allowing 'what-if' scenarios to be tested. The ETI has two such published scenarios; they are the Clockwork and Patchwork pathways. The Clockwork storyline assumes that well-coordinated, long term investment, allows new energy infrastructure to be installed like clockwork. It too favours additional nuclear, CCGT +CCS plant and renewable energy (Milne and Heaton, 2015), Fig. 2. This pathway resembles the ESME.MC pathway, nevertheless, as it is a recognised distinct ESME pathway it has been included. The Patchwork storyline sees central government taking less of a leading role and envisages a patchwork of distinct energy strategies developing at the regional level. Decarbonisation is achieved by the adoption of ad hoc renewable energy technologies including onshore and offshore wind (Milne and Heaton, 2015), Fig. 3.

2.2. Carbon plan pathways

The analysis carried out by Byers et al. (2014) modelled the water demands of six possible future electricity pathways by 2050, four taken directly from the UK Government's Carbon Plan (HM Government, 2011), [High Nuclear, High Renewables, High CCS, UK MARKAL 3.26], and two modified versions of the Carbon Plan pathways [CCS+ and UKM+], defined in Table 1.

3. Methodology

3.1. General methodology

An in-depth description of the (Byers et al., 2014) model framework, and the assumptions it makes are extensively described in that paper and will not be repeated here. However, an overview of the framework's principles is necessary, as are the additional assumptions and modifications that are made by this study (see 3.2 Applying the model).

The model framework defines a generation pathway as a series of generation outputs given in TW h for a number of given generation technologies for a number of given years. This is represented using a matrix **G** with elements n_{tg}, where **G** $=[n_t \times n_g]$, t= a given year, g = generation technology, and n_g= eight generation technologies (defined in 3.2.1 Technologies) and n_t= three yearly periods (2010, 2030 and 2050). The generation pathways used for this analysis are the ESME and Carbon Plan pathways already discussed for 2030 and 2050. For

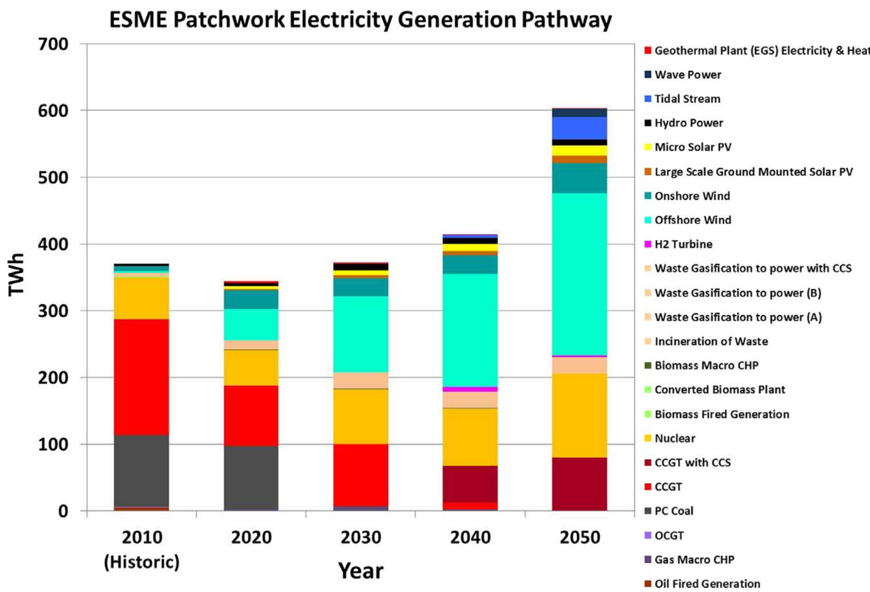

Fig. 3. ESME Patchwork Electricity Generation Pathway (Milne and Heaton, 2015).

2010 actual generation figures were used, these were taken from the Digest of UK Energy Statistics (DUKES) which provided 2010 total UK generation values per technology type (Macleay et al., 2011).

The framework then requires the distribution as a percentage of cooling water source and the distribution as a percentage of cooling method used, for each generation technology for each year to be identified. This is represented using a 4-D array **S** with elements n_{tgwm}, where **S** $=[n_w \times n_m \times n_t \times n_g]$, w = water source, m = cooling method, n_w= three cooling water sources (freshwater, estuarine and seawater), n_m = four cooling methods (once-through, evaporative, hybrid, air cooling).

Known water abstraction and consumption figures, given in ML/TW h (although this is equivalent to L/KWh), per generation technology, per cooling method can then be introduced and are represented by matrices **A** and **C** respectively with elements n_{mg}, where **A** $=[n_m \times n_g]$. For this paper matrices **A** and **C** are populated by the UK abstraction and consumption figures.

Element-wise multiplication of the arrays **GSA** and **GSC** gives total water abstraction and consumption results for each water source and cooling method combination, per generation technology for the year in question: ($Atotal_{w,m,g,t} = GAS$, $Ctotal_{w,m,g,t} = GCS$), where; $Atotal_{wmgt}$ = Total abstraction for any given combination of water source, cooling method combination, generation technology and time period, $Ctotal_{wmgt}$= Total consumption for any given combination of water source, cooling method combination, generation technology and time period.

Summation of the relevant combinations will allow total water abstraction and consumption of any given pathway generation technology, for any time period, to be calculated ($Atotal_{w,g,t} = \sum_{m=1}^{n_m} Atotal_{w,m,g,t}$, $Atotal_{g,t} = \sum_{w=1}^{n_w} Atotal_{w,g,t}$, $Ctotal_{w,g,t} = \sum_{m=1}^{n_m} Ctotal_{w,m,g,t}$, $Ctotal_{g,t}= \sum_{w=1}^{n_w} Ctotal_{w,g,t}$), where $Atotal_{w,g,t}$= total abstraction of all cooling methods for any given combination of water source, generation technology and time period. $Atotal_{g,t}$ = total abstraction of all cooling methods and water sources for any given combination of generation technology and time period. $Ctotal_{w,g,t}$= total consumption of all cooling methods for any given combination of water source, generation technology and time period. $Ctotal_{g,t}$ = total consumption of all cooling methods and water sources for any given combination of generation technology and time period.

Similarly, summation of all combinations would produce the total pathway water abstraction and consumption for any given time period ($Atotal_t = \sum_{g=1}^{n_g} Atotal_{g,t}$, $Ctotal_t = \sum_{g=1}^{n_g} Ctotal_{g,t}$). Where $Atotal_t$= total abstraction of all generation technologies using all cooling methods and water sources for any given time period. $Ctotal_t$= total consumption of all generation technologies using all cooling methods and water sources for any given time period.

3.2. Applying the model

3.2.1. Technologies

The thermal generation technologies considered by this analysis are those present in 2010 and those the ESME model and Carbon Plan pathways include in their thermal generation portfolios, namely, Nuclear (includes all large scale nuclear power plant variants), Nuclear Small/Medium Reactors (SMR), Gas (CCGT), Coal/biomass (assumed to be sub-critical), Gas CCS, Coal CCS (assumed to be super-critical unless it is IGCC), Waste Gasification and Waste Gasification CCS. Oil represents only 1.3% of all thermal generation in 2010 (Macleay et al., 2011); the ESME and Carbon Plan pathways predict by 2050 it will have been phased out. ESME also identifies geothermal technology as providing 0.25% of the UK's energy by 2050. On this basis both these technologies have been omitted from this study. ESME

Table 1
Carbon Plan Pathways.

High Nuclear	A low uptake of energy efficiency measure and CCS not being commercially viable lead to a large adoption of nuclear generation.
High Renewables	Increased uptake of renewable energy due to reduction in cost as well as increased use of energy efficiency measures, result in a generation mix of wind, solar, marine and back-up gas generation.
High CCS	CCS proves to be commercially viable resulting in a large uptake of CCS generation, largely driven by natural gas imports and exploitation of shale gas. Also assumes negative emissions through biomass CCS.
UK MARKAL 3.26	Least-cost optimised model results in a large uptake of energy efficiency measures and subsequent reduction in demand as well as a balanced generation mix including renewable energy, CCS and nuclear.
CCS+	Similar to High CCS with nuclear now replaced with further coal CCS, biomass and renewable energy.
UKM+	Similar to UK MARKAL 3.26 but with an increased energy demand met by a balanced generation mix of renewable energy, CCS and nuclear.

Table 2
Distribution of cooling method and water source, derived from (Byers et al., 2014, Schoonbaert, 2012).

Generation Technology	2010 Installed Capacity (MW)	Water Source	Cooling Method: Once-through (%)	Closed (%)	Hybrid (%)	Air (%)[a]
Nuclear	10,125	Freshwater	0	0	0	0
		Estuarine Water	15.84	0	0	0
		Sea Water	84.16	0	0	0
		Air	0	0	0	0
Nuclear SMR[b]	N/A	Freshwater	0	17	0	0
		Estuarine Water	0	41	0	0
		Sea Water	42	0	0	0
		Air	0	0	0	0
CCGT (including H2 Turbines and Anaerobic Digestion)	32,169	Freshwater	0.48	11.91	5.19	0
		Estuarine Water	20.56	13.28	19.62	0
		Sea Water	5.58	0	0	0
		Air	0	0	0	23.38
Waste Gasification[c]	N/A	Freshwater	0	68.07	0	0
		Estuarine Water	0	0	0	0
		Sea Water	0	0	0	0
		Air	0	0	0	31.93
Coal (including Biomass)	28,971	Freshwater	0	34.50	0	0
		Estuarine Water	18.32	34.00	1.38	0
		Sea Water	11.25	0	0	0
		Air	0	0	0	0.55
CCGT CCS[d]	N/A	Freshwater	0.48	11.91	5.19	0
		Estuarine Water	20.56	13.28	19.62	0
		Sea Water	5.58	0	0	0
		Air	0	0	0	23.38
Coal CCS[e]	N/A	Freshwater	0	34.50	0.00	0
		Estuarine Water	18.32	34.00	1.38	0
		Sea Water	11.25	0	0	0
		Air	0	0	0	0.55
Waste Gasification CCS[e]	N/A	Freshwater	0	34.50	0	0
		Estuarine Water	18.32	34.00	1.38	0
		Sea Water	11.25	0	0	0
		Air	0	0	0	0.55

[a] Air cooling only requires negligible volumes of water; this was assumed to be freshwater due to air cooling's use when water is scarce.
[b] Nuclear SMR distribution based on discussion with ETI and informed by ETI (2015).
[c] Waste gasification distribution calculated from all operational and consented sites as well as those in the planning process.
[d] CCGT CCS distribution the same as CCGT.
[e] Waste Gasification CCS distribution the same as Coal CCS which in turn is the same as Coal.

identifies three gas generating technologies; CCGT, anaerobic digestion, and hydrogen turbines. After email consultation with the ETI gas team (Gammer, 2015), it was agreed that the water use of these technologies would be similar. They are therefore treated as one technology, namely CCGT.

Nuclear Small/Medium Reactors (SMR) are a new technology, being smaller than traditional nuclear power stations they are anticipated to attract less rigorous siting constraints. For this reason they are classed as a separate technology.

3.2.2. *Distribution array*

To produce the array **S** for 2010, which defines how the cooling methods and water sources are distributed for a given generation technology, DUKES was first used to find the installed capacity of thermal generation power stations in the UK for 2010 > 15 MW (Macleay et al., 2011).

Neither DUKES, nor any official source, provides cooling method and water source information by power station for UK thermal generation. This was a problem Schoonbaert (2012) and Byers et al. (2014) had to resolve. This was achieved for those studies by consulting satellite imagery, online records, site visits, and contacting generation companies. Their results were now revisited and, with only minor changes, produced Table 2. Appendix A shows the raw power station data obtained. In the absence of generation information for specific power stations, their water demands were attributed relatively by using power station installed capacity. So if a CCGT power stations' rated power capacity represented 10% of the UK's total CCGT capacity, then knowing the total annual electricity generated by UK CCGT power stations it was assumed that 10% of this was generated by the power station in question, which is operated with the cooling method and water source identified-. As this assumes across each technology each power station had the same annual runtime this clearly has the potential to introduce error. In this respect it was felt that while there well may be significant errors on an individual power station basis, on average the methodology's assumption was reasonable. There was also the knowledge that a validation of the water demand methodology used for 2010 was to be carried out.

Table 2 also shows the cooling method and water source distribution for technologies not yet operational in the UK but predicted to be by 2050; they are Waste Gasification, Nuclear SMR, CCGT CCS, Coal CCS and Waste Gasification CCS. The assumptions made for these distributions are shown as a footnote to Table 2.

To determine the 2030 and 2050 cooling methods and water sources that would become used to mitigate the increasing lack of freshwater both Byers et al. (2014) and Murrant et al. (2015) accepted that one, or a combination of two possible options would from 2010 likely apply. They were either a greater use of the less water intensive cooling methods that incur higher costs and CO_2 emissions, or a greater adoption of estuarine and seawater sources would take place.

With such uncertainty it was reasoned that any UK national comparison of water demands of the study's selected pathways at 2030 and 2050 relative to 2010 can only identify an order of potential national water demand issues. In reality the availability of freshwater and seawater resource, as does the demand for power, varies significantly regionally (Mitchell and McDonald, 2015) and it is at this level of detail the real issues lie. On this basis applying the 2010 cooling distribution array relatively to 2030 and 2050 serves this paper's purpose.

3.2.3. The abstraction and consumption figures

This paper uses the abstraction and consumption figures for UK power stations, compiled by the JEP and made available by the EA. The JEP is made up of nine of the UK's leading electricity generators. The JEP has a research and development objective to understand and expand the knowledge of the environmental science and its impacts related to the generation of fossil fuel electricity (Gasparino, 2012). A specific interest is to better understand the water use of UK power stations.

Macknick et al. (2011) discusses at length the wide ranging variability found in the published subject data when attempting to consolidate the literature of water use by various electricity generation technologies in the United States. The research objective was to obtain figures that could “be incorporated into energy-economic models to estimate generation-related water use under different projected electricity portfolio scenarios”. It was found that despite significant differences in the methodologies used to compile the data it invariably resulted in wide-ranging high and low values for water abstraction and consumption. But the cooling method employed invariably produced significantly different, and definitive, water demand magnitudes. This identified that water demands of thermal power stations should be categorised by cooling method rather than generation technology.

The UK abstraction and consumption figures compiled by the JEP were based upon the Resource Efficiency Physical Index Data for 2010 and the data previously prepared for the DG Environment Blueprint. The Combustion Industry Sector and the UK Water Working Group were also consulted to help improve the quality of the data. The water use figures provided were in the form of lower and upper limits for abstraction and consumption for various generation technology and cooling method combinations. The CCS water rates provided were based on Parsons Brinckerhoff (2012). The data provided is acknowledged to be wide ranging and heavily caveated and for the purpose of this paper was not comprehensive. The variability present in the UK's abstraction and consumption data supports the view of Macknick et al. (2011) that variability in power station's water abstraction and consumption data would inevitably be found to be systemic irrespective of the country.

The UK abstraction and consumption figures shown (Tables 3a and 3b) are those required by either the ESME or Carbon Plan pathways. Some are for yet-be-developed technologies. In practice the values in the standard font are the abstraction and consumption mid-point values calculated from the range of the JEP data provided. The values in bold are calculated figures where the JEP did not provide values. The basis for calculating these unknown values was the conclusion of Macknick et al. (2011) that power station water demands are categorised by their cooling methods rather than generation technology. The JEP provided a sufficient distribution of known cooling method water demands, across a sufficient number of known generation technologies, that a ratio for different cooling methods, and different technologies across adjacent rows in Tables 3a and 3b could be found. This ratio could then be used to attribute the unknown water demands shown in bold in Tables 3a and 3b.

Waste gasification is a relatively new technology (Lightowlers, 2012), and there are no ‘working’ abstraction and consumption figures available, however the JEP do provide a value for Coal (HLF) IGCC + CCS Coal for evaporative cooling. Discussion with the ETI gas team confirmed in the absence of an actual value this would be a reasonable value to use for evaporative waste gasification + CCS (Gammer, 2015). Using the ratios now available this permits this technology's water demand under the remaining cooling methods to be determined. For waste gasification without CCS with once-through cooling, abstraction and consumption figures were determined by finding the ratio between the known non-CCS technologies and their CCS equivalents' values; as (CCGT +Coal(HLF))÷(CCGT+CCS +Coal(HLF) IGCC CCS[1]). By applying the values so obtained (abstraction: 0.72, consumption: 0.88) to the Waste Gasification + CCS with once-through cooling abstraction and consumption values, the unknown water demand for Waste Gasification with once-through cooling could be obtained. This technology's water demand under the remaining cooling methods were then once again determined using the ratios shown in Tables 3a and 3b.

Nuclear SMR is also a relatively new technology and also has no available abstraction and consumption data although IEA (2012) suggests that due to reduced efficiency water use may increase by around 5%. They also state that precise figures are not available. With this uncertainty and with the difference being relatively small it was felt more appropriate to assume that the abstraction and consumption figures would be the same as those for traditional nuclear generation.

3.3. Validation

To confirm the methodology employed does not produce unacceptable inaccuracies when modelling pathway water demands, a validation of the results obtained was carried out. The EA receives data annually showing the water abstracted but not consumed from freshwater and estuarine (not seawater) sources for power stations in England and Wales. Figures for Scotland and Northern Ireland were not available. This data for the years 2006–2010 was obtained with the main interest being 2010, the year for which the UK abstraction and consumption figures obtained apply.

Not all the EA data provided could be used as in some instances it was incomplete. The twenty-three power stations used had a total generating capacity of 29,215 MW, Table 4. This is a 42% sample of the England and Wales total installed capacity of 70,040 MW in 2010 (Macleay et al., 2011).

When matching generating technology with water demand the question arises whether for 2010 the correct choice for coal was coal Low Load Factor (LLF, capacity factor $< 46\%$), or coal High Load Factor (HLF, capacity factor $\geq 46\%$). This has a profound effect on water demand. In an exchange of correspondence with the EA their opinion was that with the large number of operational mode influences that a generating plant has to respond to (on a daily basis) with the information available there could be no definitive answer (Brierley, 2014). In line with this opinion it was decided to show the validation with both the coal LLF and coal HLF values. The results obtained for the years 2006 – 2010 are shown, Table 5.

The closest correlation for the years tested is seen to be for coal HLF, with the error for 2010, for which the UK abstraction figures relate, being just 3.23%, Table 5. When considering the HLF result over the whole validation period it is felt that whilst the error varies significantly, with the large changes in operational mode known to occur this could be expected. This result it was felt validates the

[1] Waste gasification is only selected by ESME, all coal CCS selected by ESME is IGCC pre-combustion; for consistency IGCC pre-combustion was used for this calculation rather than coal post-combustion.

Table 3a
Abstraction Factors (L/KWh),derived from (Environment Agency, 2014).

Cooling Method	Nuclear	Nuclear SMR	CCGT	Coal (HLF)	Coal (LLF)	Waste Gasification	CCGT + CCS	Coal (HLF) IGCC+CCS	Coal CCS post-combustion (HLF)	Waste Gasification CCS	Ratio
Once-through	172.85	**172.85**	79.85	160.90	217.75	**138.61**	141.35	**191.83**	259.05	**191.83**	N/A
Evaporative	7.00	**7.00**	**2.33**	3.85	5.25	**4.05**	**4.13**	5.60	**7.56**	**5.60**	0.03
Hybrid	**4.35**	**4.35**	1.45	**2.39**	**3.27**	**2.52**	**2.57**	**3.48**	**4.70**	**3.48**	0.62
Air	**0.45**	**0.45**	0.15	**0.25**	**0.34**	**0.26**	**0.27**	**0.36**	**0.49**	**0.36**	0.10

HLF: High Load factor (capacity factor ≥ 46%), LLF: Low Load Factor (capacity factor < 46%), IGCC: Integrated Gasification Combined Cycle.

Table 3b
Consumption Factors (L/KWh),derived from (Environment Agency, 2014).

Cooling Method	Nuclear	Nuclear SMR	CCGT	Coal (HLF)	Coal (LLF)	Waste Gasification	CCGT +CCS	Coal (HLF) IGCC+CCS	Coal CCS post-combustion (HLF)	Waste Gasification CCS	Ratio
Once-through	0.15	**0.15**	0.10	0.15	0.30	**0.16**	0.10	**0.18**	0.15	**0.18**	N/A
Evaporative	3.00	**3.00**	**0.96**	1.20	1.55	**1.55**	**0.96**	1.75	**1.44**	**1.75**	9.58
Hybrid	**1.88**	**1.88**	0.60	**0.75**	**0.97**	**0.97**	**0.60**	**1.10**	**0.90**	**1.10**	0.63
Air	**0.47**	**0.47**	0.15	**0.19**	**0.24**	**0.24**	**0.15**	**0.27**	**0.23**	**0.27**	0.25

HLF: High Load factor (capacity factor ≥ 46%), LLF: Low Load Factor (capacity factor < 46%), IGCC: Integrated Gasification Combined Cycle.

Table 4
Power Stations Used in Validation Process.

Power Station	Installed Capacity (MW)	Fuel Type	Water Source	Cooling Method
Little Barford	714	CCGT	FW	Evaporative
Glanford Brigg	260	CCGT	FW	Evaporative
Medway	688	CCGT	EW	Evaporative
Roosecote	229	CCGT	EW	Open loop
South Humber Bank	1285	CCGT	EW	Open loop
Killingholme A	665	CCGT	EW	Hybrid
Killingholme B	900	CCGT	EW	Hybrid
Great Yarmouth	420	CCGT	EW	Open loop
Barking	1000	CCGT	EW	Open loop
Keadby	710	CCGT	EW	Open loop
Ironbridge	940	Coal	FW	Evaporative
Eggborough	1960	Coal	FW	Evaporative
Ratcliffe	1960	Coal	FW	Evaporative
Rugeley	1006	Coal	FW	Evaporative
Drax	3870	Coal	EW	Evaporative
Kingsnorth	1940	Coal	EW	Open loop
Cottam	2008	Coal	EW	Evaporative
West Burton	2012	Coal	EW	Evaporative
Ferrybridge C	1960	Coal/ Biomass	FW	Evaporative
Fiddler's Ferry	1961	Coal/ Biomass	EW	Evaporative
Tilbury B	1063	Biomass	EW	Open loop
Hartlepool	1180	Nuclear	EW	Open loop
Oldbury	434	Nuclear	EW	Open loop
Total Capacity	29,165	N/A	N/A	N/A

FW: Freshwater, EW: Estuarine Water.

methodology's use of the UK abstraction figures to attribute, relative to 2010, the national water demands at 2030 and 2050 to the ESME and Carbon Plan pathways assessed in this study. For the 2030 and 2050 pathways both the ESME and Carbon Plan pathways provide their load factor; for ESME it is Coal LLF, for the Carbon Plan pathways it is Coal HLF (DECC, 2013). Their respective factors have been used.

With no actual consumption figures available it was not possible to validate the methodology used in regards of consumption. The consumption figures used in this analysis were provided from the same dataset as the abstraction figures and applied using the same methodology, and therefore given the validation of the abstraction figures it was felt appropriate to accept the use of the consumption figures despite being unable to directly validate them.

4. Results and discussion

4.1. ESME and Carbon Plan pathways 2030 and 2050 Water Demand

With thermal generation being the favoured means of electricity generation the current preferred technologies are Nuclear and fossil fuels +CCS, supported by renewables. For the UK the water demands this incurs at 2030 and 2050 for this study's electricity generation pathways, relative to 2010, are shown by Figs. 4–7. Regarding these figures Total Water demand refers to all water sources including freshwater, but is predominantly sea and estuarine water due to their reliance on once-through cooling. Interpreting Figs. 4–7 knowing at 2050 there will be no physical shortage of Total Water, but there will be a serious shortage of UK freshwater this clearly identifies a potential problem. In this respect it is noticeable that the ESME.MC and Clockwork pathways are Total Water intensive, while the Carbon Plan thermal generation pathways are on balance more freshwater intensive.

As would be expected the Carbon Plan's High Renewables and the ESME Patchwork pathways have lower water demands. This underlines the success high renewable pathways have in avoiding a need for large volumes of water in 2030 and 2050. In this context it should, however, be noted that even high renewable pathways have water demands that also have to be met.

4.2. Sensitivity analysis

The ESME.MC pathway with its Monte Carlo approach to uncertainty (Section 2.1.1**)** rather than producing a single result produces a range of possibilities known as simulations, normally 100. Each simulation's input is from a probabilistic range reflecting a parameter's uncertainty over the form a future UK energy system could take (Heaton, 2014). These individual simulations are then averaged to provide the mean average ESME.MC electricity generation results of Fig. 1 from which the corresponding water demands in Figs. 4–7 were calculated using this paper's methodology. The spread of the simulations is indicative of the level of uncertainty that an averaged result hides. In order to quantify this level of uncertainty a sensitivity analysis was carried out. This was achieved by calculating, as per this papers methodology, the 2030 and 2050 water abstraction and consumption demands of each of the ESME.MC pathway's simulations and showing the results in a box and whiskers form, Figs. 8–11.

Table 5
Validation Results; percentage error between modelled results and Environment Agency validation data.

Validation using Coal HLF				Validation using Coal LLF			
	Freshwater (% error)	Estuarine Water (% error)	Freshwater +Estuarine Water (% error)		Freshwater (% error)	Estuarine Water (% error)	Freshwater +Estuarine Water (% error)
2010	−3.01	3.39	3.23	**2010**	28.80	17.08	17.37
2009	3.52	14.90	14.62	**2009**	37.26	29.06	29.26
2008	23.57	−6.16	−5.58	**2008**	64.10	7.40	8.51
2007	2.12	−0.16	−0.10	**2007**	36.15	15.11	15.66
2006	12.98	19.65	19.46	**2006**	51.37	38.67	39.03
Average	7.83	6.32	6.33	**Average**	43.53	21.47	21.97

HLF: High Load factor (capacity factor ≥ 46%), LLF: Low Load Factor (capacity factor < 46%).

Figs. 8–11 show the simulations are spread more widely for 2050 than 2030 which expectedly shows there is greater uncertainty at the longer timeframe. With the exception of freshwater abstraction the distribution of all the other 2050 datasets has a wider range between the median and the minimum rather than the median and maximum. For all 2030 datasets and 2050 freshwater abstraction the opposite is the case. Therefore, for the ESME.MC pathway the mean result is more likely to be an underestimate of the 2050 datasets excluding freshwater abstraction, and an overestimate of the 2030 datasets, and the 2050 freshwater abstraction.

Table 6 shows how the first and third quartile of each dataset varies from the median. With the exception of the third quartiles of the 2030 and 2050 freshwater abstraction datasets (< 14%), all are within 10% of the median, with the majority < 7%. Table 6 then shows that the difference between the ESME.MC modelled average generation water demands of Figs. 4–7, and the median values of the data shown in Figs. 8–11, are in even closer agreement. This confirms that using the ESME.MC pathway's Monte Carlo approach of producing an average generation result from numerous simulations does provide a water demand that is representative of the individual simulations.

4.3. Comparison of USA and UK abstraction and consumption figures

Previous studies (Byers et al., 2014; Schoonbaert, 2012), that look at how the scarcity of cooling water may compromise future UK thermal energy generation used the United States' NREL data (Macknick et al., 2011). With UK abstraction and consumption figures now being available a comparison with the NREL figures used by Byers et al. (2014) is appropriate. This comparison will identify if using UK specific figures does in fact make any meaningful difference to the results obtained, Tables 7a and 7b achieve this. Due to limited NREL data for air cooling this technology's figures were not compared.

Table 7a finds for abstraction the NREL figures for the once-through, evaporative and hybrid cooling processes, underestimate the UK demand and, with the exception of nuclear generation, the difference is significant. The extent this underestimation of non-nuclear thermal generation's true abstraction water demands contributed to it being thought possible to be built inland, with freshwater cooling, is not known but this paper's results now corrects any such assumption. Table 7b shows for water consumption in most instances the opposite is found to be the case with the relative differences, while being large, relating to very much lower levels of demand.

5. Conclusions and policy implications

The aim of this paper was to use the identified ESME and Carbon Plan pathways to attribute a national water demand to the UK's predicted 2030 and 2050 thermal electricity generation policy relative to 2010. The future water demands were found to be heavily pathway dependent but, with the significant increase in the 2050 electricity demand not surprisingly the majority of pathways were found to show a significant increase in their Total and/or Freshwater demands.

This increase in water demand has policy implications and has to be judged bearing in mind that for the years to 2050 it is forecasted there will be less inland freshwater available (Hussey and Pittock, 2012;

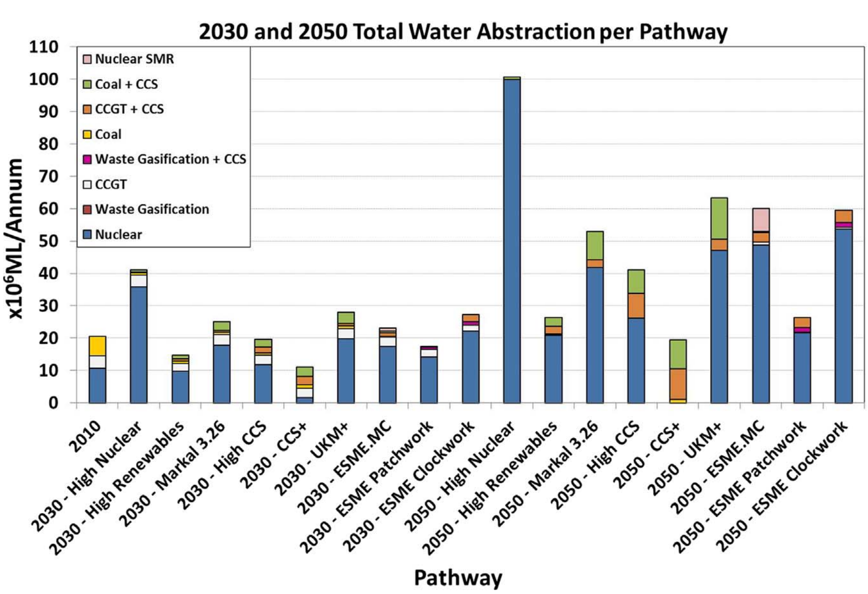

Fig. 4. 2030 and 2050 Total Water Abstraction per Pathway.

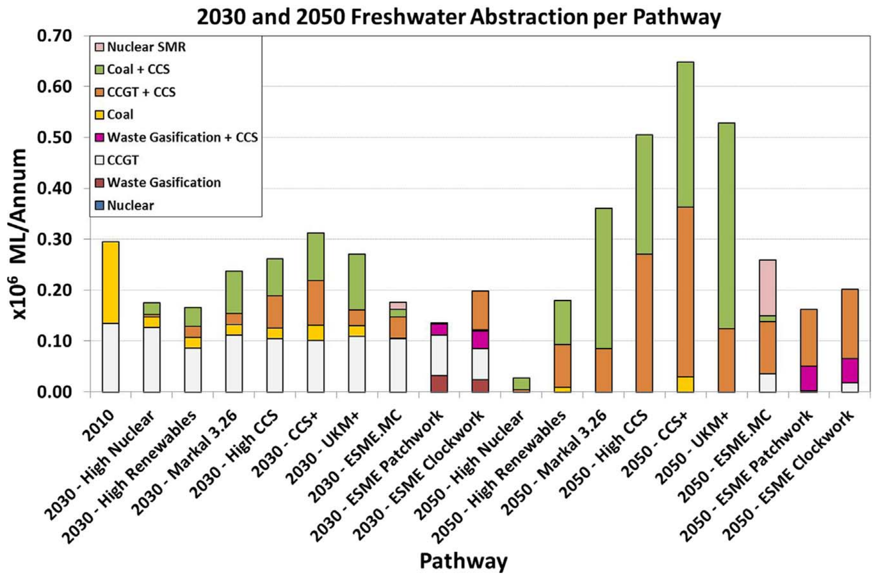

Fig. 5. 2030 and 2050 Freshwater Abstraction per Pathway.

Bouckaert et al., 2014; Wong and Johnston; , 2014). To meet the need for increased generation there is an intention to build additional thermal generation. If policymakers do not adequately recognise that thermal generation is water intensive, and that low cost generation depends on the optimum cooling water being available, then this new build has the potential to increase the UK's future generation costs. This in turn will be reflected in reducing the UK's ongoing global commercial competiveness. That the extent of this cost increase could be significant is indicated by the fact it has been shown there is already no UK inland thermal generation with a capacity greater than 150 MW that can operate with optimum cooling water (Murrant et al., 2015).

In this respect this paper's findings, especially for 2050, identifies that a future lack of water presents serious problems which generators and policy makers have to recognise. The Carbon Plan's thermal generation pathways are generally far more dependent on freshwater than those of the ESME model, with the Carbon Plan's high nuclear pathway being the exception. This higher freshwater demand is predominantly caused by a greater reliance on CCGT, or Coal with CCS. These are often seen to be inland and with a need therefore to use freshwater cooling. These stations will have to rely on the more expensive, less abstraction intensive, more consumptive evaporative and hybrid cooling methods, as well as air cooling. The ESME.MC and Clockwork pathways, with their cost optimisation goals, instead favour the cheaper coastal nuclear generation using the abstraction intensive, least-consumptive, once-through cooling method as does the Carbon Plan's high nuclear pathway. This results in high Total water, but low freshwater demand. If large volumes of Total Water were not available at the coast then the scarcity of freshwater will present policymakers with a major nuclear feasibility rethink, that is, if cost of generation remains a consideration.

While there will inevitably be scarcity issues for any 2030 and 2050 thermal generation policy that envisages employing freshwater cooling, insofar as Total Water abstraction is concerned its physical availability cannot be a limiting factor. Nevertheless, there are other considerations that can. Environmental and ecological regulation (e.g. The WFD, EU Habitats Directive) is limiting new thermal power station site availability. Under the EU Habitats' Directive thermal power stations are required to demonstrate that their activities such as, but not limited to, abstraction and discharge, do not have unacceptable impacts upon protected UK Natura 2000 sites (Environment Agency, 2012; Morris

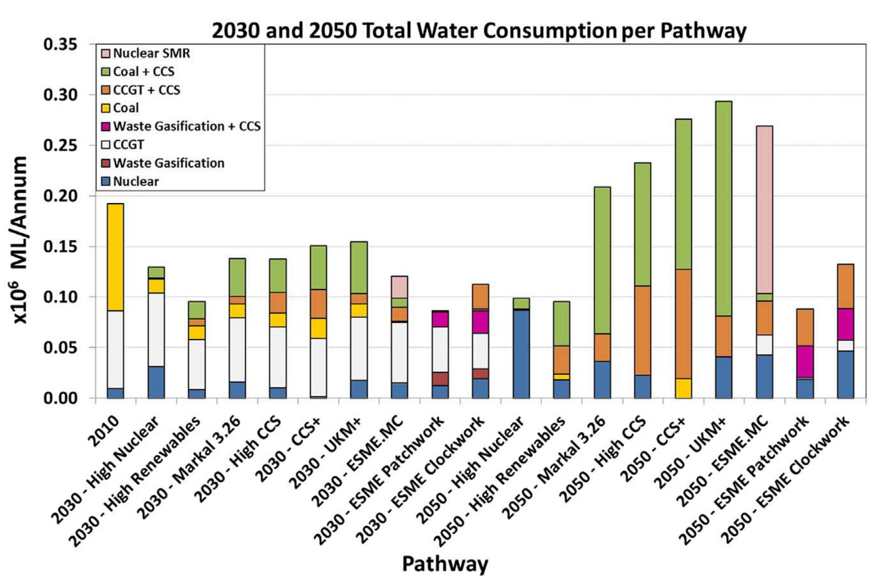

Fig. 6. 2030 and 2050 Total Water Consumption per Pathway.

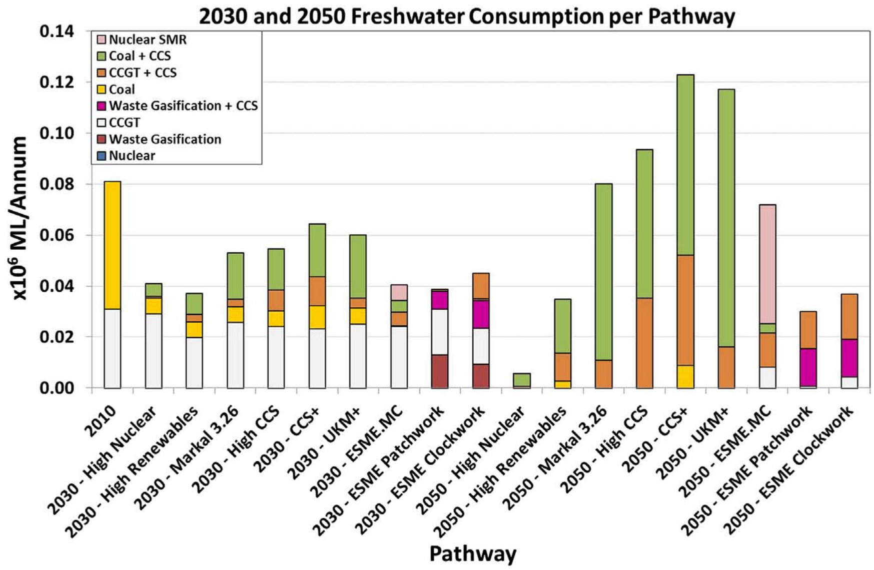

Fig. 7. 2030 and 2050 Freshwater Consumption per Pathway.

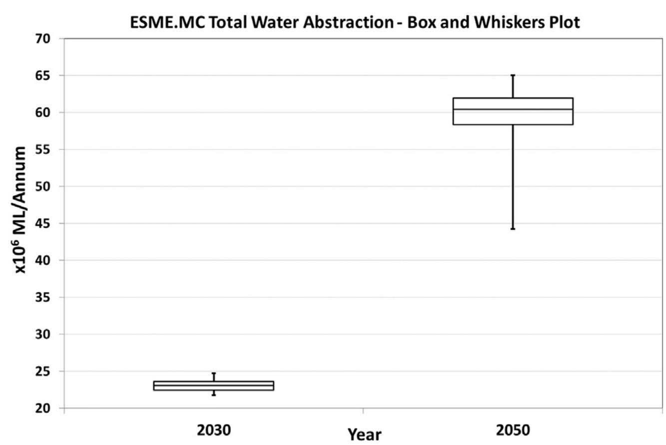

Fig. 8. ESME.MC Total Water Abstraction - Box and Whiskers Plot.

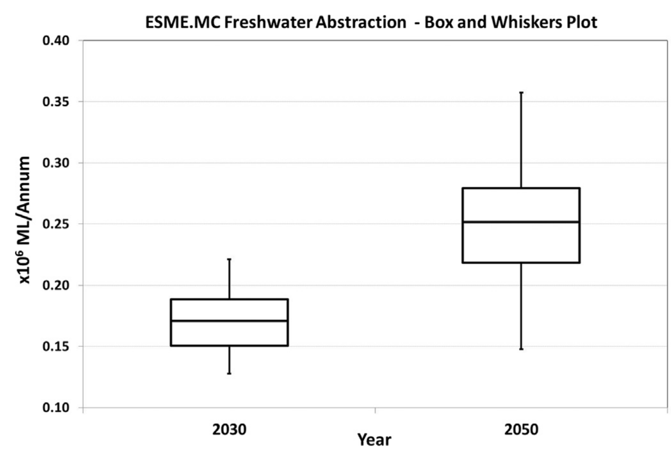

Fig. 10. ESME.MC Freshwater Abstraction - Box and Whiskers Plot.

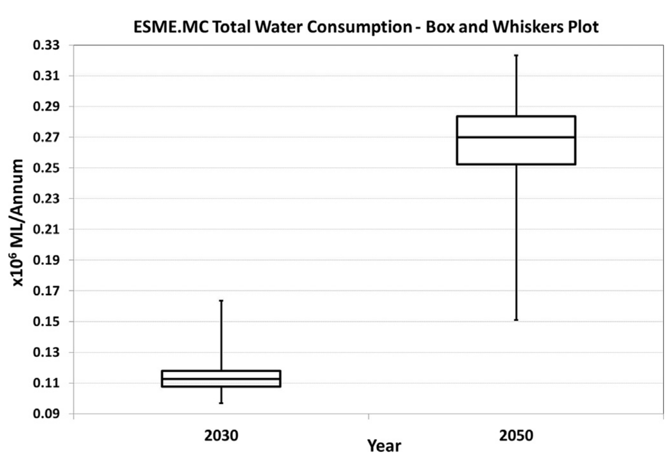

Fig. 9. ESME.MC Total Water Consumption - Box and Whiskers Plot.

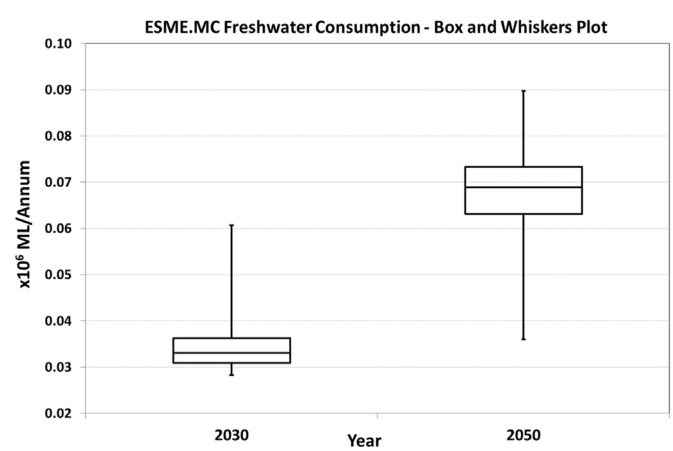

Fig. 11. ESME.MC Freshwater Consumption - Box and Whiskers Plot.

et al., 2014). Historically UK nuclear power stations have been required to reduce their load to comply with discharge thermal temperature standards (EDF Energy PLC, 2011).

Ginige et al. (2012) considered nuclear development on the Severn estuary. It found that impingement and entrainment of fauna on cooling water screens could have a significant impact on the estuary's marine ecology that could affect that water body's WFD status (Greenwood, 2008). Following a Strategic Siting Assessment the UK Government could with 7000 miles of English and Welsh coastline only identify 8 potential sites suitable for the development of nuclear power (DECC, 2011). A subsequent study undertaken by Atkins for the Department of Energy and Climate Change considered an additional 270 possible areas in England and Wales, but found only another 3 worthy of further consideration (Atkins, 2009).

Table 6
Percentage Differences from the Median.

	2030 TW Abstraction	2050 TW Abstraction	2030 TW Consumption	2050 TW Consumption	2030 FW Abstraction	2050 FW Abstraction	2030 FW Consumption	2050 FW Consumption
% Difference Between Median and Q1	−2.48	−3.44	−4.40	−6.55	−11.82	−13.16	−6.58	−8.26
% Difference Between Median and Q3	2.34	2.58	4.64	5.02	10.45	10.97	9.58	6.39
% Difference Between Median and ESME MC Average Value	−0.10	−0.73	2.00	−2.01	−0.47	0.52	4.90	−1.75

TW: Total Water FW: Freshwater.

Table 7a
Comparison of USA and UK Abstraction Factors (L/KWh).

	Nuclear			CCGT			CCGT+CCS			Coal (HLF)[a]			Coal+CCS post-combustion (HLF)[b]		
	Once-through	Evaporative	Hybrid	Once-through	Evaporative	Hybrid	Once-through	Evaporative	Hybrid	Once-through	Evaporative	Hybrid	Once-through	Evaporative	Hybrid
NREL	164	3.88	2.52	47.6	0.93	0.59	90	1.82	1.19	118	2.11	1.33	220	4.29	2.79
UK	173	7	4.45	79.85	2.22	1.45	141	4.13	2.57	161	3.85	2.39	259	7.56	4.7

HLF: High Load factor (capacity factor ≥ 46%).
[a] Coal (sub-critical).
[b] Coal +CCS (super-critical).

Table 7b
Comparison of USA and UK consumption factors (L/KWh).

	Nuclear			CCGT			CCGT+CCS			Coal (HLF)[a]			Coal+CCS post-combustion (HLF)[b]		
	Once-through	Evaporative	Hybrid	Once-through	Evaporative	Hybrid	Once-through	Evaporative	Hybrid	Once-through	Evaporative	Hybrid	Once-through	Evaporative	Hybrid
NREL	1.27	2.66	1.71	0.38	0.72	0.47	0.9	1.36	0.88	0.78	1.77	1.17	2.1	3.22	2
UK	0.15	3.06	1.88	0.1	0.96	0.6	0.1	0.96	0.6	0.15	1.2	0.75	0.15	1.44	0.9

HLF: High Load factor (capacity factor ≥ 46%).
[a] Coal (sub-critical).
[b] Coal +CCS (super-critical).

In respect of coastal planning applications, objections over visual pollution are also seen to apply to much of the UK's coastline (Boyle, 2015). It has been shown that in total these environmental and planning regulations are limiting any form of coastal thermal generation, almost everywhere. This has ominous connotations for any 2050 progressive energy policy that has to satisfy the high water intensity demands of the envisaged nuclear, or fossil fuel CCS generation, with little or no freshwater available, restricted access to sea and estuarine water resources, and still with an affordability objective. UK policy-makers must recognise all of this when they set the environmental and planning regulations thermal power stations must adhere to if they want to be sited in coastal locations.

Both the ESME Patchwork and the Carbon Plan's High Renewable pathway's generation demand at 2030 and 2050 are of the same order as for the ESME.MC and Clockwork pathways. However, their relative water demands (Figs. 4–7) find they are far less dependent on water. To this extent they provide an alternative solution to any lack of required cooling water. Their Achilles' heel, however, is at 2050 they need support from fossil fuel CCS generation, both as complimentary generation to help cover their intermittency, and to provide base load. Any renewable approach allied water intensive fossil fuel +CCS generation with freshwater would have to factor-in a high level of expensive air cooling that would quickly lead to questions about the real cost credentials of these potentially crucially important renewables' pathways.

This study uses the cooling method and water source trends of thermal power stations in 2010 to attribute national, water demands to the 2030 and 2050 ESME and Carbon Plan generation pathways. Both have pathways that are indicative of the UK's energy policy to 2050. On a comparative basis the methodology this paper used now provides an order of the increase in water demand relative to 2010 that the selected pathways at 2030 and 2050 would have. It finds that there is a serious mismatch between the current assumptions of the freshwater there will be available in the future and the likely actual availability. This mismatch will have implications for future generation costs.

This study suggests that the solution to the UK's future energy policy mismatch between thermal generation and freshwater availability is to make greater use of the UK's seawater resource. A companion paper will now consider the issues involved in doing this. It brings this paper's national generation and pathway water demands to the regional level. A methodology is developed to assess how the UK's electricity generation portfolio will change in terms of the technologies adopted, and their cost, as access to seawater is varied under Q70 and Q95 freshwater conditions. It finds the emphasis UK energy policy gives to the competing poles of low cost electricity generation and environmental protection will have significant impacts on the cost and make-up of the UK's future electricity generation portfolio.

Compliance with ethical standards

This work is funded by the Engineering and Physical Sciences Research Council and the Energy Technologies Institute. There are no conflicts of interest and the research did not involve human or animal participants.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work is funded by the Engineering and Physical Sciences Research Council and the Energy Technologies Institute. The authors would like to thank Maria Brierley from the Environment Agency for her help in obtaining validation data. The authors would also like to thank Den Gammer from the Energy Technologies Institute for his help.

Appendix A. UK power stations 2010

Station Name	Capacity (MW)	Type	Cooling source	Cooling type	Location
Aberthaw B	1586	Coal	SW	Open loop	Wales
Aberthaw GT	51	GT/OCGT	AC	Air cooled	Wales
Baglan Bay	510	CCGT	EW	Evaporative	Wales
Ballylumford B	540	GT/OCGT	AC	Air cooled	Northern Ireland
Ballylumford B OCGT	116	GT/OCGT	AC	Air cooled	Northern Ireland
Ballylumford C	616	CCGT	SW	Open loop	Northern Ireland
Barking	1000	CCGT	EW	Open loop	London
Barry	230	CCGT	AC	Air cooled	Wales
Blackburn Mill	60	CCGT	FW	Hybrid	North West
Burghfield	47	CCGT	FW	Open loop	South East
Castleford	56	CCGT	FW	Open loop	Yorkshire & the Humber
Charterhouse St Citigen London	31	GT/OCGT	AC	Air cooled	London
Chickerell	45	GT/OCGT	AC	Air cooled	South West
Cockenzie	1152	Coal	SW	Open loop	Scotland
Connahs Quay	1380	CCGT	EW	Hybrid	Wales
Coolkeeragh	408	CCGT	EW	Open loop	Northern Ireland
Coolkeeragh	53	GT/OCGT	AC	Air cooled	Northern Ireland
Corby	401	CCGT	AC	Air cooled	East Midlands
Coryton	800	CCGT	AC	Air cooled	East
Cottam	2008	Coal	EW	Evaporative	East Midlands
Cottam Development Centre	390	CCGT	EW	Hybrid	East Midlands
Cowes	140	GT/OCGT	AC	Air cooled	South East
Damhead Creek	800	CCGT	AC	Air cooled	South East
Deeside	515	CCGT	EW	Hybrid	Wales
Derwent	228	CCGT CHP	FW	Evaporative	East Midlands
Didcot A	1958	Coal	FW	Evaporative	South East
Didcot B	1430	CCGT	FW	Hybrid	South East
Didcot GT	100	GT/OCGT	AC	Air cooled	South East
Drax	3870	Coal	EW	Evaporative[1]	Yorkshire & the Humber
Drax GT	75	GT/OCGT	AC	Air cooled	Yorkshire & the Humber
Dungeness B	1040	Nuclear	SW	Open loop	South East
Eggborough	1960	Coal	FW	Evaporative	Yorkshire & the Humber
Elean	38	Biomass	AC	Air cooled	East
Enfield	408	CCGT	AC	Air cooled	London
Fawley GT	68	GT/OCGT	AC	Air cooled	South East
Fellside CHP	180	CCGT CHP	FW	Hybrid	North West
Ferrybridge C	1960	Coal/Biomass	FW	Evaporative	Yorkshire & the Humber
Ferrybridge GT	34	GT/OCGT	AC	Air cooled	Yorkshire & the Humber
Fiddler's Ferry	1961	Coal/Biomass	EW	Evaporative	North West
Fiddler's Ferry GT	34	GT/OCGT	AC	Air cooled	North West
Glanford Brigg	260	CCGT	FW	Evaporative	Yorkshire & the Humber
Grain	1320	CCGT CHP	EW	Once-through	South East
Grain	1300	GT/OCGT	AC	Air cooled	South East
Grain GT	55	GT/OCGT	AC	Air cooled	South East
Great Yarmouth	420	CCGT	EW	Open loop	East
Hartlepool	1180	Nuclear	EW	Open loop	North East
Heysham 1	1160	Nuclear	SW	Open loop	North West
Heysham 2	1220	Nuclear	SW	Open loop	North West
Hinkley Point B	870	Nuclear	SW	Open loop	South West
Hunterston B	890	Nuclear	SW	Open loop	Scotland
Immingham CHP	1240	CCGT CHP	EW	Hybrid	Yorkshire & the Humber
Indian Queens	140	GT/OCGT	AC	Air cooled	South West
Ironbridge	940	Coal	FW	Evaporative	West Midlands
Keadby	710	CCGT	EW	Open loop	Yorkshire & the Humber
Keadby GT	25	GT/OCGT	AC	Open loop	Yorkshire & the Humber
Killingholme A	665	CCGT	EW	Hybrid	Yorkshire & the Humber
Killingholme B	900	CCGT	EW	Hybrid	Yorkshire & the Humber
Kilroot	520	Coal	SW	Open loop	Northern Ireland
Kilroot OCGT	142	GT/OCGT	AC	Air cooled	Northern Ireland
King's Lynn	99	CCGT	AC	Air cooled	East
Kingsnorth	1940	Coal	EW	Open loop	South East

Kingsnorth GT	34	GT/OCGT	AC	Air cooled	South East
Knapton	42	GT/OCGT	AC	Air cooled	Yorkshire & the Humber
Langage	905	CCGT	AC	Air cooled	South West
Little Barford	714	CCGT	FW	Evaporative	East
Little Barford GT	17	GT/OCGT	AC	Open loop	East
Littlebrook GT	105	GT/OCGT	AC	Air cooled	South East
Longannet	2304	Coal	EW	Open loop	Scotland
Marchwood	842	CCGT	EW	Open loop	South West
Medway	688	CCGT	EW	Evaporative	South East
Oldbury	424	Nuclear	EW	Open loop	South West
Peterborough	405	CCGT	AC	Air cooled	East
Peterhead	1180	CCGT	SW	Open loop	Scotland
Ratcliffe	1960	Coal	FW	Evaporative	East Midlands
Ratcliffe GT	34	GT/OCGT	AC	Air cooled	East Midlands
Rocksavage	810	CCGT	FW	Evaporative	North West
Roosecote	229	CCGT	EW	Open loop	North West
Rugeley	1006	Coal	FW	Evaporative	West Midlands
Rugeley GT	50	GT/OCGT	AC	Air cooled	West Midlands
Rye House	715	CCGT	AC	Air cooled	East
Saltend	1200	CCGT	EW	Evaporative	Yorkshire & the Humber
Sandbach	50	CCGT	FW	Evaporative	North West
Seabank 1	812	CCGT	EW	Hybrid	South West
Seabank 2	410	CCGT	EW	Hybrid	South West
SELCHP (South East London CHP)	32	Waste	AC	Air cooled	London
Severn	848	CCGT	AC	Air cooled	Wales
Shoreham	400	CCGT	EW	Open loop	South East
Shotton	210	CCGT CHP	AC	Air cooled	Wales
Sizewell B	1191	Nuclear	SW	Open loop	East
Slough	61	Biomass	FW	Evaporative	South East
South Humber Bank	1285	CCGT	EW	Open loop	Yorkshire & the Humber
Spalding	880	CCGT	AC	Air cooled	East Midlands
Staythorpe C	1724	CCGT	FW	Evaporative	East Midlands
Steven's Croft	50	Biomass	AC	Air cooled	Scotland
Sutton Bridge	819	CCGT	AC	Air cooled	East
Taylor's Lane GT	132	GT/OCGT	AC	Air cooled	London
Teeside CCGT	1875	CCGT	EW	Evaporative	North East
Teeside Power station	45	CCGT	FW	Evaporative	North East
Thetford	39	Biomass	AC	Air cooled	East
Thornhill	50	CCGT	FW	Open loop	Yorkshire & the Humber
Tilbury B	1063	Biomass	EW	Open loop	East
Tilbury GT	68	GT/OCGT	AC	Air cooled	East
Torness	1190	Nuclear	SW	Open loop	Scotland
Uskmouth	363	Coal/Biomass	EW	Hybrid	Wales
West Burton	2012	Coal	EW	Evaporative	East Midlands
West Burton CCGT	1270	CCGT	EW	Evaporative	East Midlands
West Burton GT	40	GT/OCGT	AC	Air cooled	East Midlands
Wilton 10	38	Biomass	EW	Hybrid	North East
Wilton GT 2	42	GT/OCGT	AC	Air cooled	North East
Wilton Power Station Coal/biomass	150	Coal/Biomass	FW	Evaporative	North East
Wilton Power Station Gas	130	GT/OCGT	FW	Air cooled	North East
Wylfa	960	Nuclear	SW	Open loop	Wales

FW: Freshwater, EW: Estuarine Water, SW: Seawater, AC: Air Cooling.

References

Atkins, 2009. A consideration of alternative sites to those nominated as part of the Government's Strategic Siting Assessment process for new nuclear power stations. Epsom UK.

Bouckaert, S., Assoumou, E., Selosse, S., Maïzi, N., 2014. A prospective analysis of waste heat management at power plants and water conservation issues using a global TIMES model. Energy 68, 80–91.

Boyle, D., 2015. Nuclear power stations should be designed to be beautiful to get the public on side, says energy secretary. Dly. Mail Online, (6 June 2015).

Brierley, M., 2014. 9th September 2014. *RE : UK Power Stations Water Consumption Data*. Type to MURRANT, D.

Byers, E.A., Hall, J.W., Amezaga, J.M., 2014. Electricity generation and cooling water use: uk pathways to 2050. Glob. Environ. Change 25, 16–30.

Byers, E.A., Qadrdan, M., Leathard, A., Alderson, D., Hall, J.W., Amezaga, J.M., Tran, M., Kilsby, C.G., Chaudry, M., 2015. Cooling water for Britain's future electricity supply. In: Proceedings of the Institution of Civil Engineers - Energy, 168, 188-204.

Csereklyei, Z., et al., 2016. The effect of economic growth, oil prices, and the benefits of reactor standardization: Duration of nuclear power plant construction revisited. Energy Policy 91, 49–59.

Committee On Climate Change, 2015. Fifth Carbon Budg.: step Towards a Low.-Carbon Econ..

Day, G., 2012. Modelling the UK energy system: practical insights for technology development and policy making. Available: ⟨http://eti.co.uk/downloads/related_documents/2012_12_10_GD_Modelling_the_UK_energy_system_FINAL.pdf⟩.

DECC, 2011. In: CHANGE, D.F.E.A.C. (Ed.), National Policy Statement for Nuclear Power Generation (EN-6).. The Stationery Office, London.

DECC, 2013. 2050 Pathways [Online]. Available: ⟨https://www.gov.uk/guidance/2050-pathways-analysis⟩ Accessed 26 April 2016 .
DECC, 2015. Amber Rudd's speech on a new direction for UK energy policy [Online]. Department for Energy and Climate Change. Available: ⟨https://www.gov.uk/government/speeches/amber-rudds-speech-on-a-new-direction-for-uk-energy-policy⟩ Accessed 26 April 2016 .
Edf Energy Plc, 2011. Report on Adaptation Under the Climate Change Act 2008: EDF Energy Adaptation Report 2011. London, UK.
Energy Technologies Institute, 2016. Technologies and Strategy: ESME [Online]. Available: ⟨http://www.eti.co.uk/project/esme/⟩ (accessed 26 April 2016) 2016).
Environment Agency, 2012. *Hinkley Point C Appropriate Assessment for related Environment Agency permissions* [Online]. Available: ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/301540/gesw0712bwtl-e-e.pdf⟩.
Environment Agency, 2014. UK Power Stations Water Consumption Data. Type to Murrant, D.
European Commission, 2001. Integrated Pollution Prevention and Control (IPPC) Reference Document on the application of Best Available Techniques to Industrial Cooling Systems. European Commission.
Gammer, D., 2015. *RE : Water Use of Gas Technologies*. Type to MURRANT, D.
Gasparino, U., 2012. Independent development of water use in scenarios for future thermal power stations. Jt. Environ. Program..
Ginige, T., Ball, F., Thornton, A., Caine, C., 2012. Nuclear power: ecologically sustainable or energy hotpotato? A case study. Int. J. Liabil. Sci. Enq. 5, 183–198.
Government, H., 2011. *The air quality strategy for England, Scotland, Wales and Northern Ireland: Volume 1* [Online]. Available: ⟨https://www.gov.uk/government/publications/the-air-quality-strategy-for-england-scotland-wales-and-northern-ireland-volume-1⟩ (accessed January 2016).
Greenwood, M.F.D., 2008. Fish mortality by impingement on the cooling-water intake screens of Britain's largest direct-cooled power station. Mar. Pollut. Bull. 56, 723–739.
Gu, A., Teng, F., Wang, Y., 2014. China energy-water nexus: Assessing the water-saving synergy effects of energy-saving policies during the eleventh five-year plan. Energy Convers. Manag. 85, 630–637.
Heaton, C., 2014. Modelling Low-Carbon Energy Sytem Designs with the ETI ESME Model. Energy Technologies Institute.
Hm Government, 2011. The Carbon Plan: delivering our low carbon future. HM Government, London.
Hussey, K., Pittock, J., 2012. The Energy-Water Nexus: managing the Links between Energy and Water for a Sustainable Future. Ecol. Soc., 17.
IEA, 2012. Efficient Water Management in Water Cooled Reactors. International Atomic Energy Agency. [Online]. Available: ⟨http://www-pub.iaea.org/books/iaeabooks/8883/Efficient-Water-Management-in-Water-Cooled-Reactors⟩ (accessed 27 December 2016).
Lightowlers, P., 2012. *Will gasification finally take off?* [Online]. Environmental Data Services. Available: ⟨http://www.mineralandwasteplanning.co.uk/news/1163564/will-gasification-finally-off⟩ (accessed 2 March 2015).
Macknick, J., Newmark, R., Heath, G., Hallett, K.C., 2011. A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies. National Renewable Energy Laboratory, Colorado, USA.
Macleay, I., Harris, K., Annut, A., 2011. Digest of United Kingdom Energy Statistics 2011. Department of Energy and Climate Change, London.
Milne, S., Heaton, C., 2015. Options, Choices, Actions; UK scenarios for a low carbon energy system transition. Energy Technologiew Institute.
Mitchell, G., Mcdonald, A., 2015. Developing resilience to England's future droughts: time for cap and trade? J. Environ. Manag. 149, 97–107.
Morris, R.K.A., Bennett, T., Blyth-Skyrme, R., Barham, P.J., Ball, A., 2014. Managing Natura 2000 in the marine environment – An evaluation of the effectiveness of 'management schemes' in England. Ocean Coast. Manag. 87, 40–51.
Murrant, D., Quinn, A., Chapman, L., 2015. The water-energy nexus: future water resource availability and its implications on UK thermal power generation. Water Environ. J. 29, 307–319.
Murrant, D., Quinn, A., Chapman, L., 2016. Water Use UK Therm. Electr. Gener. Fleet 2050: Part 2 Quantifying Probl..
Pacsi, A.P., Alhajeri, N.S., Webster, M.D., Webber, M.E., Allen, D.T., 2013. Changing the spatial location of electricity generation to increase water availability in areas with drought: a feasibility study and quantification of air quality impacts in Texas. Environ. Res. Lett. 8, 035029.
Parsons Brinckerhoff, 2012. Parsons Brinckerhoff 2012 Water Demand for Carbon Capture and Storage (CCS). Bristol.
Schoonbaert, B., 2012. The water-energy nexus in the UK: Assessing the impact of UK energy policy on future water use in thermoelectric power generation. Water: Science and Governance, Kings College, University of London.
The Royal Academy of Engineering, 2011. Institution of civil engineers, institution of chemical engineers, the institution of engineering and technology & institution of mechanical engineers. Infrastructure, Engineering and Climate Change Adaptation – ensuring services in an uncertain future.
Tran, M., Hall, J., Hickford, A., Nicholls, R., Alderson, D., Barr, S., Baruah, P., Beavan, R., Birkin, M., Blainey, S., Byers, E., Chaudry, M., Curtis, T., Ebrahimy, R., Eyre, N., Hiteva, R., Jenkins, N., Jones, C., Kilsby, C., Leathard, A., Manning, L., Otto, A., Oughton, E., Powrie, W., Preston, J., Qadrdan, M., Thoung, C., Tyler, P., Watson, J., Watson, G., Zuo, C., 2014. National infrastructure assessment: Analysis of options for infrastructure provision in Great Britain. UK Infrastructure Transitions Research Consortium.
Turnpenny, A.W.H., et al., 2010. Cooling Water Options for the New Generation of Nuclear Power Stations in the UK, Bristol, UK.
Wong, K.V., Johnston, J., 2014. Cooling systems for power plants in an energy-water nexus era. J. Energy Resour. Technol.-Trans. ASME 136, 6.